Final Report
Project Title: SAMS Research and Development

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LONG-TERM GOALS

The goal of this project was to develop and transition new technologies and operational procedures to support the successful use of Autonomous Underwater Vehicles (AUVs) in the deep sea and in shallow coastal waters throughout the world.

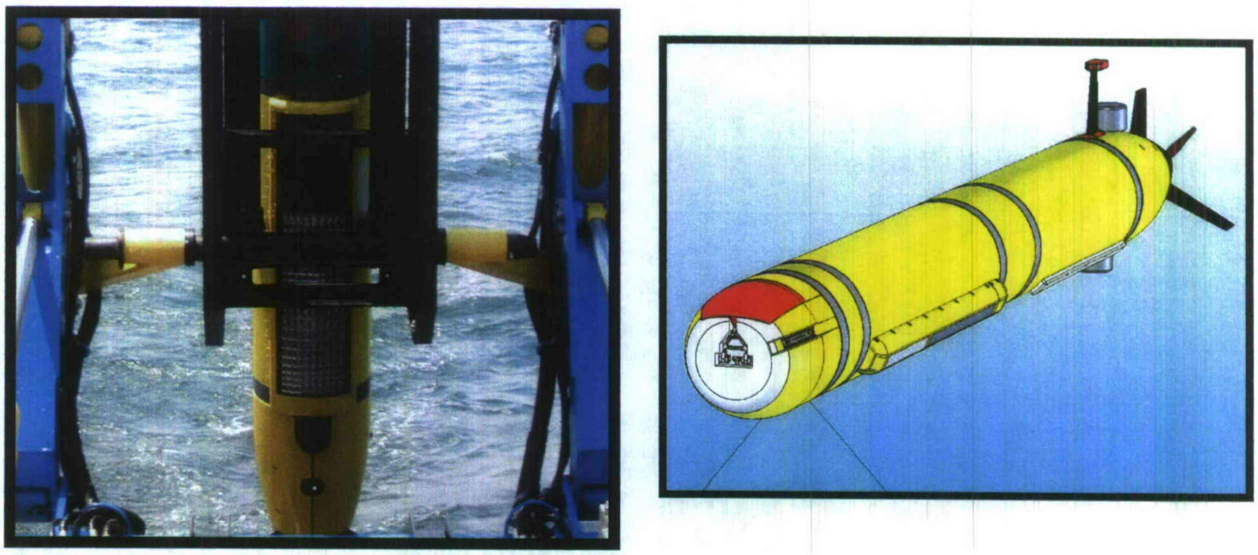


Figure 1: New REMUS-3000 vehicle with low frequency acoustics and LED lighting

OBJECTIVES

The objectives of this research included:

1. **Long-standoff and leave behind operations**: Analytic estimates and at-sea tests were performed to establish the baseline performance of the REMUS 3000 and 6000 systems for long-range standoff and leave behind scenarios involving multiple vehicles. The goal of this effort was to pursue those changes in both the vehicle systems and operational doctrine required to provide a robust and operationally viable capability.

2. **Navigation and Communication Beacons**: Under this task WHOI developed and tested new low-frequency, long-range navigation and communication beacon solutions to enhance multi-vehicle operations in long-standoff and leave-behind scenarios. These beacons will not only act as transponders that support multiple vehicle operations, they may also include the ability to receive messages via the acoustic modem and then retransmit or forward these messages to another beacon, surface ship, or vehicle.

3. **Inertial Navigation**: Under this task opertional procedures were developed that optimized the performance of an inertial navigation system when operated in both deep and shallow water.

4. **Vehicle Operating System**: Under this task we evaluated the benefits and drawbacks of migrating the REMUS family of vehicles to a new operating system. This research has resulted in follow-on funding to implent the development effort required to migrate the REMUS vehicle software to VxWorks, a modern real-time operating system.

5. **Low Light LED Imaging**: Under this task we performed experimentation towards the application of pulsed high power LEDs and commercially available low light imaging sensors to underwater imaging. This project led to follow on funding to complete the development of the new 4-Mpixel electronic imaging system used on the REMUS-3000 and REMUS-6000 vehicles.

APPROACH

This program involved at-sea experimentation with multiple autonomous underwater vehicle systems that operate in communication/navigation networks or with complete autonomy. The data obtained from these experiments has provided the Navy with a proven, robust, and operationally viable set of guidelines for performing high resolution long stand-off and leave behind survey missions in the open ocean or in littorals.

WORK COMPLETED

1. During FY06 and FY07, research was performed to explore concepts and system improvements required to achieve greater autonomy with small UUV systems. This included modifications to an exiting REMUS 600 vehicle to be configured with two 5 kW-hr battery packs, a high resolution CTD sensor, and a sidescan sonar. Multiple experiments were performed to analyze the performance of the inertial navigation system for use on long-term submerged operations. A number of revisions to the system design and interface to the INU have been made to improve the performance of the system. Long missions were performed and inertial navigation drifts rates of 0.1% of distance traveled were realized.

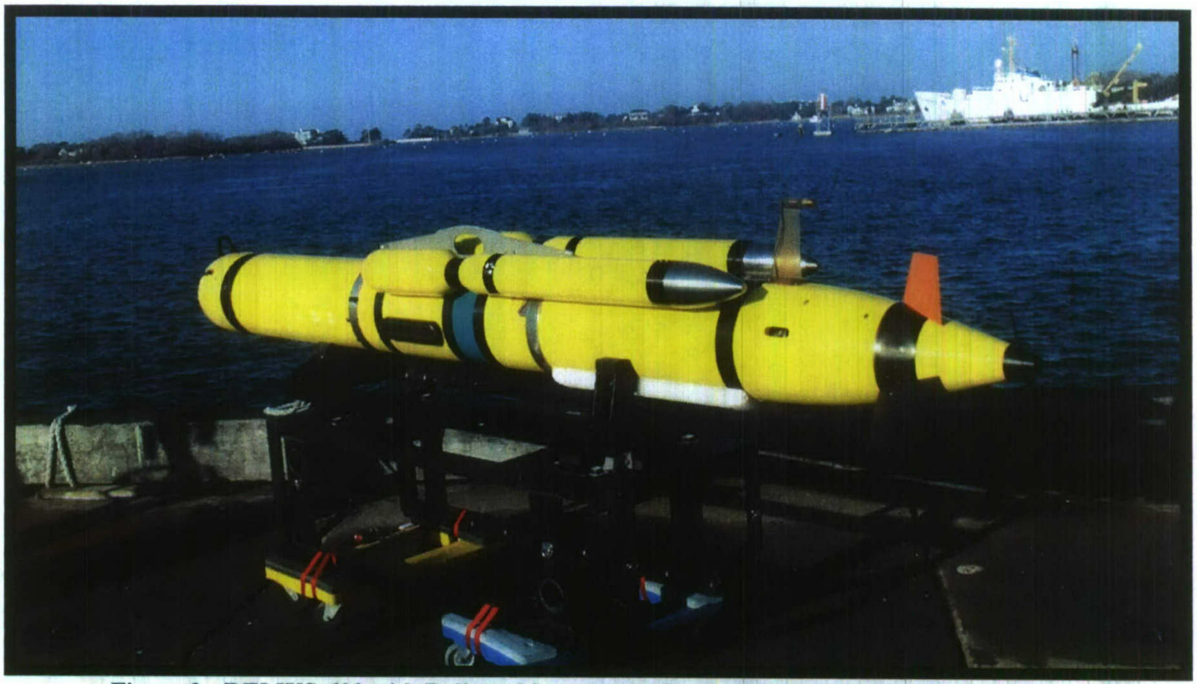


Figure 2: REMUS-600 with Deliverable transponders and LED Array Imaging Panels

2. During FY06 and FY07, research was performed on the deep ocean navigation and control beacons. The design of these beacons is based on the previously developed medium-frequency (20-30 kHz) digital acoustic transceiver which is the core of the REMUS-100 vehicle system acoustic navigation and tracking systems. A new version of low frequency transceivers has been developed, as well as a new low frequency carrier board which allows simple integration of the digital transceiver and the micro-modem into an integrated low-frequency acoustic system. This new design shares a single transducer between the acoustic transponder and acoustic modem electronics, simplifying the design and lowering the cost as compared to separate systems. This technology allowed for the development of a similar deliverable version (funded separately) which will allow a vehicle such as the REMUS-3000 to carry an acoustic beacon in transit, and deploy it in the survey area as a navigation aid, thus allowing indefinite submerged operations without the need to surface periodically for GPS navigation updates.

3. Also during FY06 and FY07, a new LED-based illumination system was created based on the preliminary research accomplished in this project. This project has culminated in the development and fabrication of low-profile lighting panels for electronic still imaging of the seafloor from UUV's. The lighting panels consist of a high-density array of approximately 100 LED's with individual reflectors. The array is computer designed to uniformly illuminate the rectangular image field of the camera at the typical imaging altitude. The array panels are

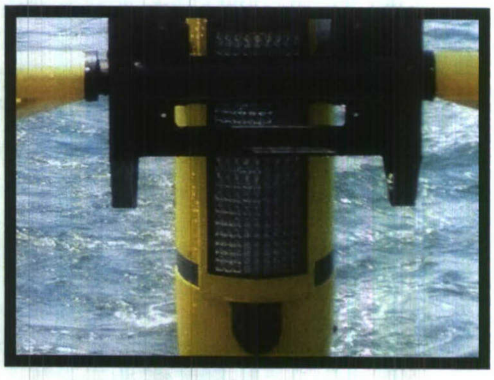


Figure 3: LED Panel installed on REMUS-3000

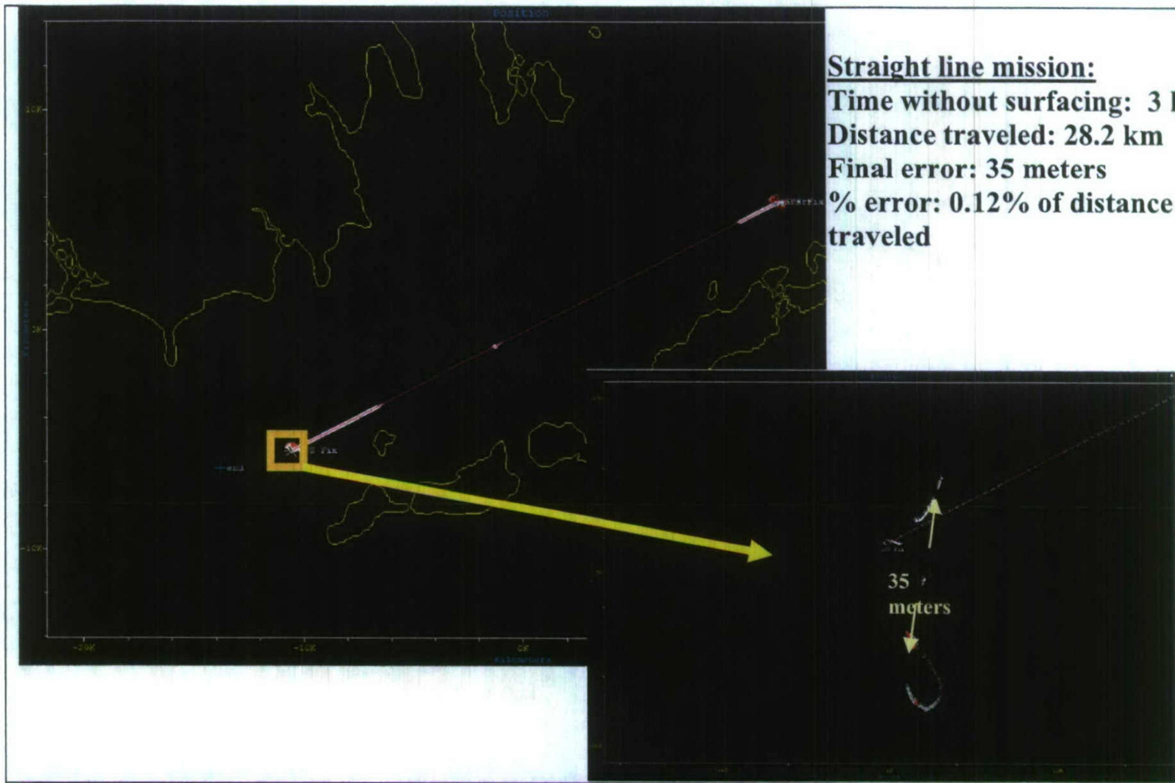
designed as modules that attach to the underside of the vehicle. This research has already resulted in follow on funding from the Naval Oceanographic Office to develop a next-generation panel that will contain 400-500 individual LEDs, taking advantage of recent developments in commercial LED technology. In addition to the hardware development, the new LED panels have allowed us to develop new imaging capabilities that capitalize on the rapid pulse controllability of the LED vs. that of a Xenon strobe. This new capability will provide the UUV operator with leg-by-leg programmability of imaging resolution, and frame rate, from widely spaced high resolution images to continuous, strobed low-resolution video.

RESULTS

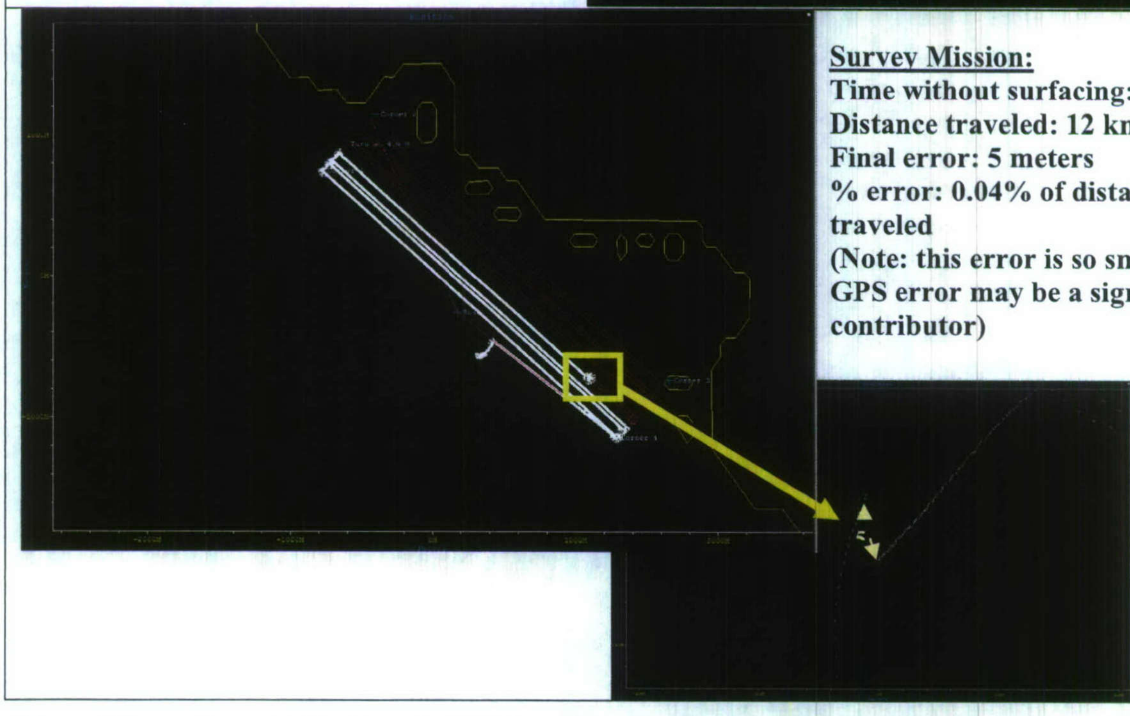
Statistics describing the typical inertial navigation error growth were collected. Typical errors achieved in the long, straight-line missions were approximately 0.15% of distance traveled. Errors of 0.05% of distance traveled were common in missions small area survey missions because the DC errors in velocity and heading estimates tend to cancel in the turns. Higher errors occurred on some missions which have been attributed to sensor problems, in particular due to poor sound velocity estimation due to low quality conductivity and temperature measurements. For this reason, we have recently replaced the original REMUS-600 CT sensor with the new, higher fidelity NBOSI (Neil Brown Ocean Sensors, Inc.) CT probe, which has greatly improved accuracy and bandwidth specifications. Prototype testing of the LED strobe system components have verified operation at pressure and peak power output characteristics.

IMPACT/APPLICATIONS

The research has helped to improve the expected performance of a mine counter measure system that forms an operation lane from well off shore to the beach. In addition, this research will increase the capability to operate in deep water with multi-vehicle capable acoustic transponders/acomms nodes. This development has spread into other programs including the new low frequency deliverable transponder. The new developments in high density LED-array illumination for deep water electronic still imaging will soon outdate xenon strobe technology for many applications. This technology will provide higher quality imaging at lower input power levels than traditional xenon strobe lighting. The pulse length and modulation control will allow greater exposure control, video frame rate flash syncronizations, and power control. A new, multi-tasking operating system will upgrade the capabilities of the REMUS vehicles, allowing simpler integration of new software modules and improved networking capabilties.



Straight line mission:
Time without surfacing: 3 hours
Distance traveled: 28.2 km
Final error: 35 meters
% error: 0.12% of distance traveled



Survey Mission:
Time without surfacing: 2.25 hours
Distance traveled: 12 km
Final error: 5 meters
% error: 0.04% of distance traveled
(Note: this error is so small that GPS error may be a significant contributor)

Figure 4 Error observed after long straight-line mission is typically greater than the errors observed during survey type missions of similar lengths. This is due to the natural error cancellations that occur when turning, in both along-track (speed error) and across track (heading error).

TRANSITIONS

Already much of the long-mission inertial navigation research and system improvements developed have transitioned into other Navy programs and commercial systems. Further transition is expected of all aspects of this research. The deep, low-frequency acoustic beacons will likley transition directly into deep ocean survey operations of the Naval Oceanographic Office, as will the new LED lighting technology. These developments address key technical issues affecting current Navy operations.

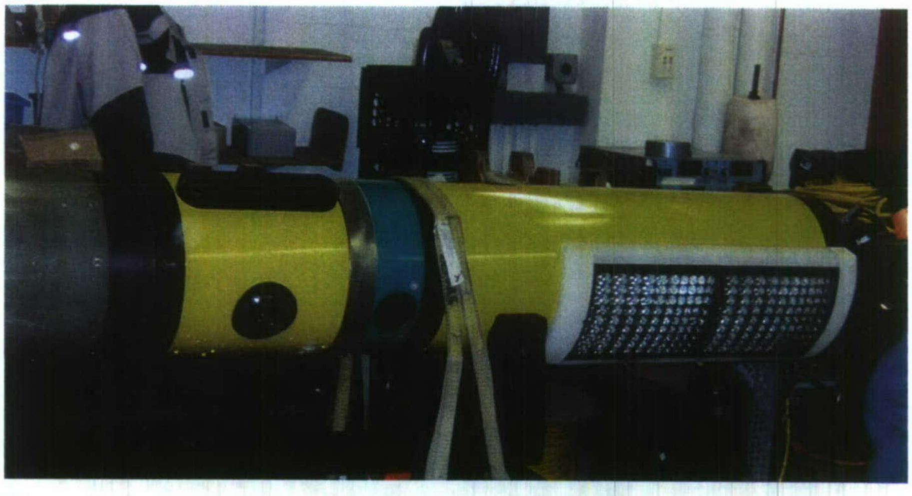


Figure 5: New Electronic Imaging System with LED Illuminator developed for and installed on REMUS-600 with Laser Scalar Gradiometer for shallow water MCM.

RELATED PROJECTS

Acoustic and Magnetic Detection, Localization, and Classification of Proud and Buried Mines Using Light Weight AUV's, Co-Principal Investigators: Thomas Austin and Roger Stokey, Woods Hole Oceanographic Institution, ONR Award Number: N00014-07-1-0064. This project utilized the new electronic imaging technology developed here to incorporate an optical imaging capability to the REMUS-600 for shallow water mine reconnaissance.

REMUS-3000 Development: Co-Principal Investigators: C. von Alt and T. Austin, for the Naval Oceanographic Office, This project also used the new LED imaging technology.

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14. ABSTRACT
This program involved at-sea experimentation with multiple autonomous underwater vehicle systems that operate in communication/navigation networks or with complete autonomy. Also included was research and development efforts towards the creation of new technological advancements in undersea optical imaging and navigation. The data obtained from these experiments has provided the Navy with a proven, robust, and operationally viable set of guidelines for performing high resolution long stand-off and leave behind survey missions in the open ocean or in littorals.

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